Resolution of the neutron lifetime puzzle

and the Conceptual Design of its Experimental Confirmation

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- The lifetime of free neutrons is *puzzling*: in the **beam** experiments ($\tau_{beam} = 888.0 \pm 2.0$ s) it is greater than in the **trap** experiments ($\tau_{trap} = (877.75 \pm 0.28_{stat} + 0.22/-0.16_{syst})$ s, e.g., according to Gonzalez et al 2021) well beyond the error margins.
- It would have been explained by the **two-body decay** into a **hydrogen atom** plus antineutrino if the Branching Ratio (BR) – compared to the usual three-body decay – would be ~ 1%: in the **beam** experiments they count only the protons from the three-body decay and **miss the two-body decay.**
- However, the previously known theoretical BR (for such two-body decay) was much smaller: $4x10^{-6}$.

Gonzalez et al, Phys. Rev. Lett. 127 (2021) 162501

- Alternatively, Fornal and Grinstein (2018) suggested that neutron might decay into an *unspecified* dark matter (DM) particle.
- The problem still was that the resulting hypothetical DM particle was not identified.
- Moreover, Dubbers et al (2019) showed that the BR for this process is at least several times smaller than required 1%.
- In 2024 experiment by Joubioux, Savajols et al with the hypothetical dark decay $^{6}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + n + \chi$, the corresponding BR for free neutrons was shown to be $\sim 10^{-5}$, while BR ~ 1% is needed for reconciling τ_{trap} and τ_{beam}.

Fornal and Grinstein, Phys. Rev. Lett. 120 (2018) 191801

Dubbers et al, Phys. Lett. B 791 (2019) 6

Joubioux, Savajols et al, Phys. Rev. Lett.

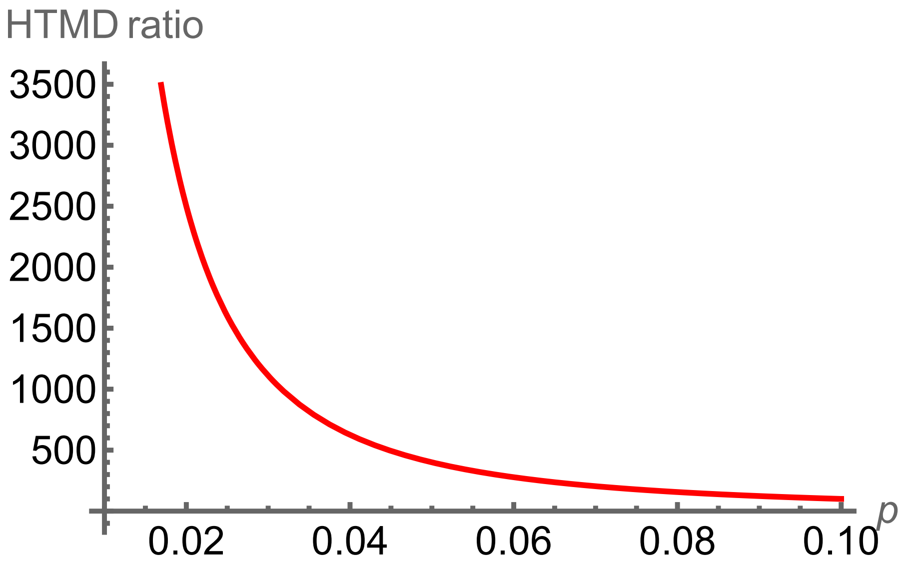
- In our papers [4, 5] of 2024, we brought to the attention of the research community that with the allowance for the second solution of Dirac equation for hydrogen atoms, **the theoretical BR for the decay into a hydrogen atom** (plus antineutrino) **is increased by a factor of 3300, that it to 1.3%.**
- This is in the **excellent agreement with "experimental" BR = (1.15 ± 0.27)%** required for reconciling the above τ_{trap} and τ_{beam}.
- Thus, it seems that the allowance for the above, enhanced two-body decay of free neutrons solves the neutron lifetime puzzle ***completely***.
- Below are some details.

[4] Oks 2024 *New Astronomy* **113** 102275

[5] Oks 2024 *Intern. Review Atom. Molec. Phys.* **15** 49

But first: how the second solution of Dirac equation for hydrogen atoms became legitimate?

- Analysis of atomic experiments related to the distribution of the linear momentum in the ground state of hydrogen atoms revealed a huge discrepancy.
- Namely, the ratio of the experimental and previous theoretical results was up to *tens of thousands* (J. Phys. B: At. Mol. Opt. Phys. **2001**, *34*, 2235).



- This figure shows the **ratio** of the theoretical High-energy Tail of the linear Momentum Distribution (HTMD), calculated by Fock (1935), to the experimental HTMD deduced from the analysis of atomic experiments for a great variety of collisional processes between hydrogen atoms and electrons or protons (Gryzinski, 1965) – versus the linear momentum p.
  (The linear momentum p is in units of $m_e c$,)
- It is seen that the relative discrepancy between the theory and experiments can reach many orders of magnitude: **3 or 4 orders of magnitude (!)** – in the relevant range of p: $m_e e^2/\hbar < p << m_e c$.
- Namely, the **experimental HTMD falls off much-much slower** than the theoretical one.

Fock, *Z. Physik* **1935**, *98*, 145

Gryzinski, *Phys. Rev.* **1965**, 138, A336

- This was the motivation behind our *theoretical* results from that paper of 2001 in the JPB.
- The standard Dirac equation of quantum mechanics for hydrogen atoms has two analytical solutions: 1) a *weakly singular* at small r; 2) a *more strongly singular* at small r.
- For the ground state, the radial part of the coordinate wave functions is

$$R_{0,-1}(r) \propto 1/r^{q}, \qquad q = 1 \pm (1 - \alpha^2)^{1/2}.$$

- Here α is the fine structure constant; – 1 in the subscript of the wave function $R_{0,-1}$ is the eigenvalue of the operator $K = \beta(2\mathbf{Ls} + 1)$ that commutes with the Hamiltonian (β is the Dirac matrix of the rank 4).
- So, the 1st solution has only weak singularity: $q \approx \alpha^2/2 \approx 0.000027$ (the “regular” solution, for brevity).
- The 2nd solution is really singular ($q \approx 2$) and is usually rejected (the normalization integral diverges at $r = 0$).

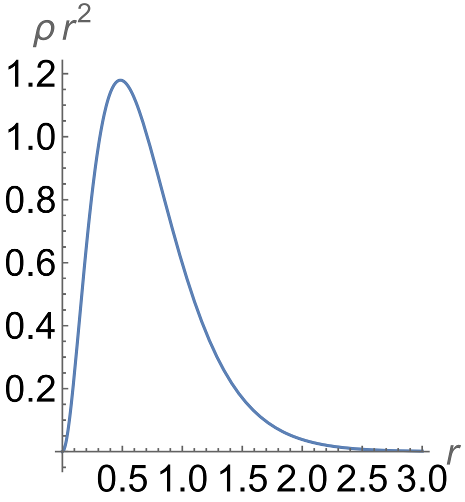
- The situation changes after allowing for the finite nuclear size.
- For models where the charge distribution inside the nucleus (the proton) is assumed to be either a charged spherical shell or a uniformly charged sphere, the 2nd solution outside the proton is justifiably rejected: it cannot be tailored with the corresponding regular solution inside the nucleus.
- In that paper of 2001 in the JPB, we derived a **general class of potentials inside the nucleus**, for which the singular solution outside the nucleus can be actually tailored with the corresponding regular solution inside the nucleus at the boundary.
- In particular, this class of potentials includes those corresponding to the charge density distributions that have a **peak at r = 0.**
- From experiments on the elastic scattering of electrons on protons (see, e.g., Simon et al (1980) and Perkins (1987)), it is known that the charge density distribution inside protons does have a **peak at r = 0.**

Simon et al, *Nucl. Phys.* **1980**, *A333*, 381

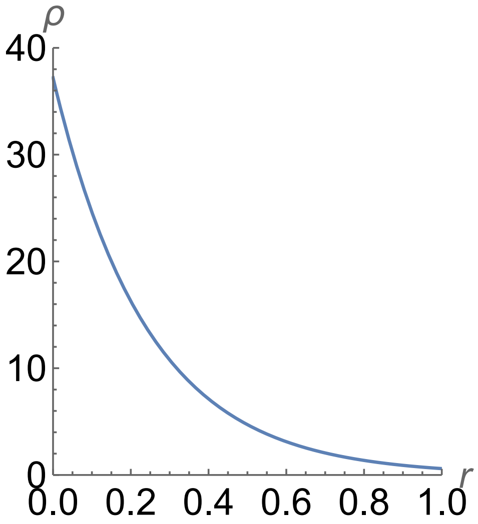
Perkins, *Introduction to High Energy Physics*; Addison-Wesley: Menlo Park, CA, USA, 1987, Sect. 6.5.

The top figure: the experimental charge distribution $r^2\rho(r)$ in protons

(*The Frontiers of Nuclear Science, A Long Range Plan*, DOE/NSF, Nuclear Science Advisory Committee (2008))



The bottom figure: the experimental charge **density** distribution $\rho(r)$ in protons – it does have the peak at r = 0.



- Thus, the regular solution inside the proton can be tailored with the singular solution outside the proton at the boundary.
- So, in that paper of 2001 in JPB, we derived analytically the corresponding wave function.
- As a result, the huge multi-order **discrepancy** between the experimental and theoretical HTMD got **completely eliminated**.
- The reason: for the singular solution outside the proton, a much stronger rise of the coordinate wave function toward the proton at small r translates into a *much slower fall-off* of the wave function in the p-representation for large p (according to the properties of the Fourier transform) than the scaling ~ $1/p^6$ predicted by Fock (1935).

Oks, *J. Phys. B: At. Mol. Opt. Phys.*, **2001**, *34*, 2235

- The corresponding derivation in that paper of 2001in JPB used *only* the fact that in the ground state the eigenvalue of the operator K is $k = -1$.
- Therefore, actually the corresponding derivation is valid not just for the ground state, but for any state of hydrogen atoms characterized by the quantum number $k = -1$.
- Those are S-states ($l = 0$), specifically $^2S_{1/2}$ states.
- So, both the regular exterior solution and the singular exterior solution are legitimate for ***all*** S-states.
- Both solutions are legitimate also for the $l = 0$ states of the *continuous* spectrum.
- All of these additional results were presented in our paper of 2020 in *Research in Astronomy and Astrophysics* (**2020**, *20(7)*, 109) published by the British IOP Publishing, where we applied these results to solving one of the dark matter puzzles.

- This second kind of hydrogen atoms having only the S-states was later called the Second Flavor of Hydrogen Atoms (SFHA). Here is why:
- Both the regular and singular solutions of the Dirac equation outside the proton correspond to **the same energy**.
- Since this means **the additional degeneracy**, then according to the fundamental theorem of quantum mechanics, there should be an **additional conserved quantity**.
- In other words: hydrogen atoms have ***two flavors*, differing by the eigenvalue of this additional, new conserved quantity**: hydrogen atoms have *flavor symmetry* (Oks, *Atoms* **2020**, 8, 33).
- It is called so **by analogy with quarks that have flavors**: for example, there are up and down quarks.
- For representing this particular quark flavor symmetry, there was assigned an operator of the additional conserved quantity: the isotopic spin I – the operator having two eigenvalues for its z-projection: $I_z = 1/2$ assigned to the up quark and $I_z = -1/2$ assigned to the down quark.

- Thus, the elimination of the huge multi-order discrepancy between the theoretical and experimental distributions of the linear momentum in the ground state of hydrogen atoms constituted **the first experimental evidence of the existence of the SFHA** – since no alternative explanation for this huge discrepancy was ever provided.
- There are also **three additional experimental evidences** from three *<u>different</u>* kinds of atomic experiments:

- from electron impact excitation of hydrogen atoms
- from electron impact excitation of hydrogen molecules
- from charge exchange between low energy protons and hydrogen atoms.

- For all them, the SFHA-based explanation removed large discrepancies (up to a factor of two or more) between the experimental and previous theoretical results, while alternative explanations were never provided.
- **So, the SFHA does exist.**

- **THE PRIMARY FEATURE of the SFHA**: since the SFHA have only the $l = 0$ states, then according to the well-known selection rules of quantum mechanics, the **SFHA do not emit or absorb the electromagnetic radiation** – **they remain DARK** (with the exception of the 21 cm line resulting from the transition between the hyperfine sublevels of the ground state)

- **More details**: due to the selection rules, all matrix elements (both diagonal and non-diagonal) of the operator **d** of the electric dipole moment are zeros.
- For this reason, the SFHA do not couple not only to the dipole radiation, but also to the quadrupole, octupole, and all higher multipole terms – because multipoles contain linear combinations of various powers of the radius-vector operator **r** of the atomic electron, which yield zeros in all orders of the perturbation theory.
- For the same reason, the SFHA cannot exhibit multi-photon transitions.
- This is because multi-photon transitions consist of several one-photon virtual transitions, each step being controlled by a matrix element of **r**, but all these matrix elements are zeros.

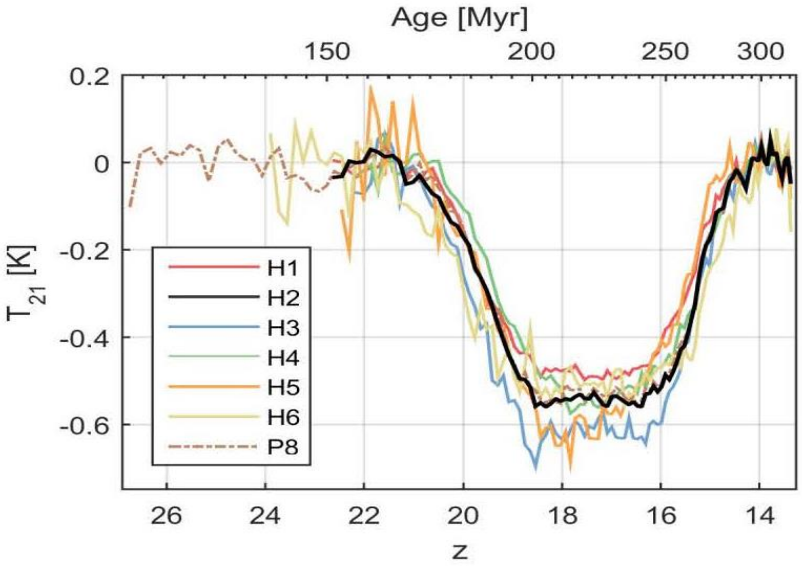
VERY IMPORTANT

- For the above reasons, the SFHA does not react to a static electric field or a laser field – no static or dynamic Stark effect.
- Therefore, **the SFHA cannot be ionized by** a static electric field or by a laser field.

- There is also an astrophysical evidence that SFHA exists.
- There is a perplexing observation by Bowman et al (2018) of the anomalous absorption in the (redshifted) 21 cm line from the early Universe.
- The absorption signal was found to be ***2 to 3 times stronger*** than predicted by the standard cosmology.

Bowman et al, *Nature* **2018**, *555*, 67

This Figure shows the observed absorption signal in the red-shifted 21 cm spectral line versus the cosmological red shift $z = \lambda_{obs}/\lambda_{rest} - 1$. Different curves correspond to different statistical processings of the signal.



- This indicated that the hydrogen gas temperature was **significantly smaller** than predicted by the standard cosmology.
- Barkana (2018) suggested that some *unspecified dark matter* particles provided an additional cooling of the hydrogen gas by collisions.
- By his estimates, the quantitative explanation of the above anomalous absorption required the mass of unspecified dark matter particles to be ~ baryons masses: **unspecified baryonic dark matter particles**.
- Thereafter McGaugh (2018) examined the results by Bowman et al (2018) and Barkana (2018) and came to the same conclusion: the explanation of the anomalous absorption requires **baryonic dark matter particles**.

Barkana, *Nature* **2018**, *555*, 71

McGaugh *Research Notes of the Amer. Astron. Soc.* **2018**, 2, 37

- In that paper of 2020 in Research in Astronomy and Astrophysics (British Publisher IOP) we considered the following: what if these unspecified dark matter particles were the SFHA?
- It should be noted that the SFHA would also contribute to the 21 cm line, while remaining dark otherwise.
- In that paper it was explained that in the course of the expansion of the Universe, the SFHA decouple from the cosmic microwave background radiation (due to having only the $l = 0$ states) **earlier** than the usual hydrogen atoms.
- For this reason, their spin temperature (controlling the absorption signal in the 21 cm line) was smaller than for the usual hydrogen atoms.
- This explained the observed anomalous absorption both qualitatively and quantitatively, and made the **SFHA a compelling candidate for the baryonic dark matter**.

Oks 2020 *Research in Astronomy and Astrophysics* **20** 109

- **Important: the theory of the SFHA is based on the standard quantum mechanics (the Dirac equation). It does not go beyond the Standard Model and does not resort to changing the physical laws –in distinction to the overwhelming majority of dark matter theories.**
- Besides, the existence of the SFHA is *evidenced by 4 different types of atomic/molecular experiments*.
- **The "Occam razor principle"** dictates that **when several theories compete, the one that makes less assumptions *is the most probable to correspond to reality***.
- Thus, the Occam razor principle favors the **existing** SFHA as as explanation of the observed anomalous absorption in the 21 cm line.

- Now: back to the **neutron two-body decay**.
- Its probability P_{ns} is proportional to the square modulus of the electron wave function at the nuclear surface R (see, e.g., Bahcall 1961 Phys. Rev. 124, 495):

$$P_{ns} = \mathrm{const}\ |\Psi_{ns}(R)|^2,$$

where $\Psi_{ns}(R)$ *is the value of the atomic electron wave function at* $r = R$ ("const" is the normalization constant whose specific value is immaterial for obtaining the ratio of probabilities below).

- We focus on the formation of hydrogen atoms in the ground state 1S since this has the overwhelming probability:

$$P_{1s} = \mathrm{const}\ |\Psi_{1s}(R)|^2.$$

- In the mixture of the SFHA with usual hydrogen atoms in the ratio ε to 1, outside the proton, the radial part of the Dirac bispinor for the ground state (based on Eq. (17) from paper of 2001 in the JPB), can be written in the following form for f- and g-components (where all quantities are in the natural units $\hbar = m_e = c = 1$):

$$f(r, \varepsilon) \approx -\beta^{5/4} \{1 + \varepsilon\Delta/(2\beta^2 r^2)]\}/(1 + \varepsilon^2)^{1/2},$$

$$g(r, \varepsilon) \approx 2\beta^{3/4} \{1 + \varepsilon\Delta/(4\beta^2 r)]\}/(1 + \varepsilon^2)^{1/2},$$

$$\Delta = E_0 - E = -4\beta^{3/2} \int_0^R [V_{inter}(r) + 1/r] r^2 dr.$$

Here $\beta = \alpha^2$, α being the fine structure constant; E_0 and E are the unperturbed (R = 0) and the perturbed (R > 0) energies, respectively; $V_{inter}(r)$ is the potential inside the proton, corresponding to the **experimental charge distribution inside the proton** from work [15].

- This equation is valid for $R \leq r << 1/\alpha$.

[15] *The Frontiers of Nuclear Science, A Long Range Plan*, DOE/NSF, Nuclear Science Advisory Committee (2008) and arXiv:0809.3137 (2008)

- Then the probability of the neutron two-body decay becomes:

$$P(R, \varepsilon) = \text{const}\ [f(R, \varepsilon)^2 + g(R, \varepsilon)^2].$$

- Now we calculate the ratio of the probability $P(R, \infty)$, corresponding to the SFHA without any usual hydrogen atoms, to $P(R, 0)$, corresponding to the usual hydrogen atoms without the SFHA:

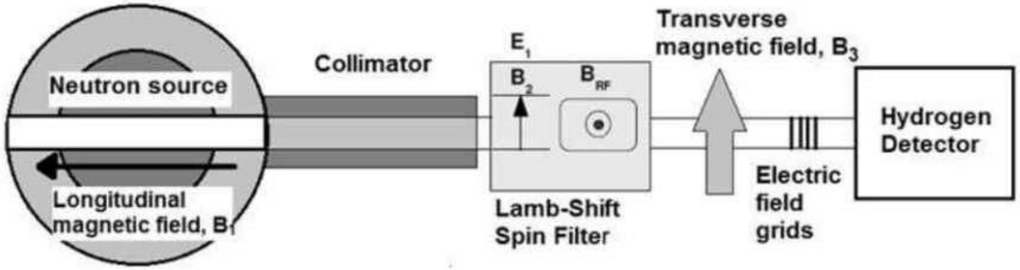
$$\rho = P(R, \infty)/P(R, 0).$$

- On substituting the numerical value of $\beta \approx 0.0000533$ and $R \approx 0.00218$ (the latter being translated in the natural units from $R = 0.84$ fm), we obtain:

$$\boldsymbol{\rho \approx 3300}.$$

- Thus, **the outcome of the two-body decay of the neutron is – with the overwhelming probability – the SFHA**, rather than the usual hydrogen atom.
- Physically, this is because the 2nd solution wave function rises toward the proton much faster than the 1st solution wave function: at the proton boundary $|\Psi(R)|_{2nd}/|\Psi(R)|_{1st} \approx 57.$

- So, the theoretical BR, being increased by a factor of 3300, becomes (1.3 ± 0.3)%.
- This is in the excellent agreement with "experimental" BR = (1.15 ± 0.27)% required for reconciling the above τ_{trap} and τ_{beam}.
- Thus, it seems that the above, significantly enhanced two-body decay of neutrons solves the neutron lifetime puzzle *completely*.
- **I propose the design of the experiment** that will constitute both **the first experimental detection of the 2-body decay of neutrons** and the **experimental confirmation that the 2-body decay of neutrons produces overwhelmingly the SFHA** – ***as follows***.



- We can use as the starting point the design suggested by McAndrew et al (2014).
- The neutrons decay inside the through-going beam tube.
- The hydrogen atoms then pass through the collimator. (The Lamb-shift spin filter is optional, not mandatory).
- A transverse magnetic field B_3 then removes a large number of the three-body decay protons and electrons from the beam line.
- **THE CENTRAL POINT (my suggestion): then, the resulting hydrogen atoms should be subjected to a relatively strong the electric field (a static field or a laser field) able *to ionize the usual hydrogen atoms*.**
- **The SFHA cannot and will not be ionized by this field, as explained above.**
- Further details are in the next slides.

McAndrew et al, Phys. Procedia 51 (2014) 37

- The experiment should consist of the following **two modes**.
- In the 1st mode, the ionizing electric field should not be applied: **the hydrogen detector will count all hydrogen atoms – both the SFHA and the usual hydrogen atoms**.
- In the 2nd mode, the ionizing electric field should be applied: the usual hydrogen atoms will get ionized, but the SFHA will not get ionized: **the hydrogen detector will count only the SFHA atoms**.
- Then the results of the hydrogen detector in the 1st and 2nd modes should be compared with each other.
- **THE CENTRAL POINT**: **If the 2-body decay of neutrons produces overwhelmingly the SFHA, then the results of the hydrogen detector in the 1st and 2nd modes would be approximately the same** (i.e., the approximately the same number of hydrogen atoms detected).
- If in the 1st mode there would be detected much more hydrogen atoms than in the 2nd mode, this would mean zero or little of the SFHA produced by the 2-body decay of neutrons.

- Some more details on the proposed experiment
- The usual hydrogen atoms can be ionized from the ground state by the Nd:YAG laser of the wavelength 1064 nm, as it was done in experiments, e.g., by Rotvliege and Shakeshaft (PRA **41** (1990) 1609).
- The laser intensity in the above experiment was ~ **10^{14} W/cm^2**
- By now laser intensities ~ 10^{21} W/cm^2 are achieved; so, the Nd:YAG laser providing ~ 10^{14} W/cm^2 is readily available from commercial sources.
- As for the detector of hydrogen atoms, it could be based, for example, on the proposal by Zhang et al (2022) to count the hydrogen atoms by using a microcalorimeter.

Zhang et al, 2022 https://arxiv.org/abs/2210.02314

- Alternatively: there have been many trap devices used for the experiments at the ILL in Grenoble, but they counted neutrons without flushing out protons.
- If it would be possible for any of the above trap devices to add the feature for flushing out protons – by applying the graduated electric potential (as in the beam experiment by Nico et al, Phys. Rev. C 71 (2005) 055502) or by applying the transverse magnetic field (as in the proposed experiment by McAndrew et al, 2014) – then perhaps one of these trap devices could be also a starting point for the experiment that I suggest.
- That is, after flushing out protons, then to subject the hydrogen atoms of both kinds to a relatively **strong the electric field (a static field or a laser field)** able ***to ionize the usual hydrogen atoms*****.**
- Then to perform the experiment in two modes: without the ionizing electric field and with the ionizing electric field – and to compare the hydrogen atoms count in the two modes.
- **If the 2-body decay of neutrons produces overwhelmingly the SFHA, then the results of the hydrogen detector in the 1st and 2nd modes would be approximately the same.**

- A week ago I made the one-hour seminar presentation of the above results (in many more details) at the ILL in Grenoble.
- There was a very enthusiastic response and the willingness to perform the suggested experiment at the ILL.
- I hope my presentation here, Orsay would motivate other experimental groups to perform such experiment and/or to help the ILL to perform it.

Few final slides (before Conclusions):

COSMOLOGICAL CONSEQUENCES

- The above results lead to viewing neutron stars in a new light: as the generators of the baryonic DM in the Universe, as presented in our paper of 2024 in New Astronomy (v. 113, 102275).
- There are 3 relevant situations.
- First, at the surface of **old neutron stars** (of ages ~ 10^7 years or older, the surface temperature being ~ 1 eV or smaller [16]), neutrons decay and release the decay products into the star atmospheres.
- Through the secondary decay channel (of the branching ratio ~ 1%) neutrons release the SFHA (plus antineutrinos).
- Since the temperature is ~ 1 eV or smaller, the resulting SFHA can survive and slowly accumulate in the atmospheres of old neutron stars.
- Second, **in the neutron stars, whose mass becomes slightly less than ~ 0.1 of the solar mass**, there occurs the explosive process of the hydrodynamic destruction of these neutron stars [17].
- As a result, these neutron stars throw neutrons into the interstellar medium, where they decay through the two channels discussed above.
- In the warm interstellar medium (neutral or ionized) and in H II regions, where the temperature is ~ 1 eV or smaller, the resulting SFHA survive and slowly accumulate.

[16] Gonzalez and Reisenegger, Astron. Astrophys. 522 (2010) A16

[17] Blinnikov et al, Sov. Astron. 34 (1990) 595

- Third, mergers of a neutron star with another neutron star or with a black hole are accompanied by the ejection of neutron-rich material ([18-20].
- This mechanism potentially can also lead to the formation of SFHA as the ejecta cools down.
- Thus, in all 3 situations, **neutron stars could slowly generate new *specific, described in detail* baryonic DM in the form of the SFHA.**
- There is an **observational astrophysical evidence** of this, as follows.

[18] Shibata and Hotokezaka, Annu. Rev. Nucl. Part. Sci. 69 (2019) 1
[19] Radice et al, Annu. Rev. Nucl. Part. Sci. 70 (2020) 95
[20] Fernandez et al, Class. Quantum Grav. 34 (2017) 154001

- In the course of the Universe evolution, the usual hydrogen atoms and the SFHA formed **at the end of the recombination epoch** (at 370 000 years of the Universe age)
- The most detailed map of the cosmic microwave background, from which the Plank Collaboration deduced the existence of the baryonic DM **in the ratio 1:5** to the non-baryonic DM [21], also refers to the end of the recombination epoch.
- So, first of all, **the baryonic DM does exist**.

[21] Arbey and Mahmoudy, Progr. Part. Nucl. Phys. 119 (2021) 103865

- Second, for non-baryonic DM, the most favorable candidate is considered to be **axions** [22].
- In the cores of DM halos, **axion stars** are expected to form [23].
- Above a critical mass, these axion stars **explosively decay**, emitting, in particular, radio photons [24-28].
- Thus, the mass of non-baryonic DM (in the form of axions) **gradually decreases with time**.

[22] Review by Ringwald, Proc. of Sci. 081 (2016)

[23] Tkachev, Phys. Lett. B261 (1991) 289

[24] Escudero et al, Phys. Rev. D 109 (2024) 043018

[25] Di, Eur. Phys. J. C 84 (2024) 283

[26] Du et al, Phys. Rev. D 109 (2024) 043019

[27] Chung-Jukko et al, Phys. Rev. D 108 (2023) L061302

[28] Levkov et al, Phys. Rev. D 102 (2020) 023501

- However, from astrophysical observations follows that the ratio of total DM to the usual matter was about factor of 5 at the end of the recombination epoch and **still is about factor of 5 at the current epoch** – see, e.g., Siegel [32].
- This means that the mass of baryonic DM should gradually **increase** with time – to compensate for the gradual decrease of non-baryonic DM mass with time.
- The only one mechanism (to the best of our knowledge) for increasing the baryonic DM mass with time is the generation of the SFHA by neutron stars, as described above.
- Therefore, the above situation could be construed as the indirect evidence of the existence of this mechanism [33].

[32] Siegel (2022) https://bigthink.com/starts-with-a-bang/dark-matter-decaying-dark-energy/

[33] Oks, New Astronomy (2024), accepted.

CONCLUSIONS

- With the allowance for the second solution of Dirac equation for hydrogen atoms (whose existence is evidenced by four different types of atomic/molecular experiments and by astrophysical observations), the **theoretical BR for the two-body decay of neutrons into hydrogen atoms** (plus antineutrinos) **increased by a factor of 3300 to (1.3 ± 0.3)%.**
- **This is in the excellent agreement with "experimental" BR = (1.15 ± 0.27)%** required for reconciling the above τ_{trap} and τ_{beam}.
- Thus, it seems that the above enhanced two-body decay of neutrons solves the neutron lifetime puzzle ***completely***.
- **I propose the design of the experiment** that will constitute both **the <u>first</u> experimental detection of the 2-body decay of neutrons** and the **experimental confirmation that the 2-body decay of neutrons produces <u>overwhelmingly</u> the SFHA**.
- Such decay is also the mechanism by which **neutron stars are slowly producing baryonic dark matter** in the form of the SFHA.
- There is an **astrophysical evidence of the existence of this mechanism**.

Thank you for your attention

Merci pour votre attention